Potential for Reducing CO2 Emissions in the Operation of Subcritical Power Plants into Supercritical

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***Abstract*— The consumption of electricity that increase anytime also increases CO_2 emissions in the air as a result of coal combustion flue gas at the power plant. The operation of supercritical boilers on the power plant will lead to higher thermal efficiency compared to subcritical boilers. Higher steam pressure boiler will increase the thermal efficiency and automatically reduce CO_2 emissions due to a reduction in fuel consumption at the same boiler efficiency and heating value of coal. At 166.9 bar subcritical steam boiler thermal efficiency was 45.47 % and CO_2 emissions were 602.2 tons while at supercritical pressure 240 bar, efficiency increased to 47.12 % with a reduction in CO_2 emissions of 20.9 tons to 581.3 tons.**

Keywords—subcritical, supercritical, CO_2 emission.

I. INTRODUCTION

Electricity demand continues to increase anytime, it requires an adequate electricity supply. Coal fired steam power plant is one with the largest supply, more than 50 %. Most power plants in Indonesia still use coal fuel because economically it is the cheapest. The International Energy Agency (IEA) (2009) estimates that CO_2 emissions from energy use in cities will grow by 1.8% per year between 2006 and 2030 [1]. However, the use of coal fuel will cause carbon emissions, especially CO_2 which is very large, and become one of the biggest contributors to Greenhouse Gases. Each electricity production with coal fuel every 1 kWh produces an average CO_2 gas emissions of 1.05 kg [2], while in [3] CO_2 emissions are 964 gr / kWh. This value is higher than in diesel power plants with emissions of 541 g per kWh [3]. The emissions per unit of electricity are estimated to be in the range of 0.91 to 0.95 kg/kWh for CO_2[4].

Although the use of coal is sensitive to environmental issues, its use is massive in more than 100 countries due to reasons of supply, ease of transportation, and relatively cheaper prices than other fuels [5]. An accurate calculation of CO_2 emissions from coal fired power plant is one of the prerequisites for the realization of carbon emission reduction [6].

In this study, analyzing the thermodynamic flow in a reference power plant, and calculating CO_2 emissions. Power plant that already have fuel consumption data and have measured fuel quality (proximate analysis or carbon content) can use method-2 [7]. The actual power plant which is still working in subcritical conditions, is simulated into supercritical conditions, and calculated the potential for fuel savings and CO_2 emissions reduction.

Power plants with supercritical boilers operating above critical points for water 22.12 MPa and 647.14 K pressure and temperature respectively [8]. Operation of the plant with supercritical boilers will result in higher thermal efficiency compared to the use of subcritical boilers. Higher thermal efficiency will lead to smaller CO_2 emissions, for example in subcritical generators CO_2 emissions of 850 kg / MWh, whereas in supercritical plants smaller emissions are 800 kg / MWh [9] . Simulations by [10] and empirical studies of 600 MW capacity plants in China [11] also showed smaller CO_2 production in power plants with supercritical technology.

Research on reducing CO_2 emmisions in power plant has been done, mitigation to reduce emissions, using CCS (Carbon Capture and Storage) technology, will unfortunately increase the cost of generating 30-70% and reduce efficiency up to 14% [12]. One of CCS applications is oxy-fuel combustion, where coal is burned in a mixture of pure oxygen and recycled exhaust gas with a high content of CO_2 gas [13]. Another method is post combustion technology, namely by mounting the membrane captures <90% CO_2 [14]. Pre combustion method requires 75-125% higher generation costs than not using CCS technology [15].

Efforts to reduce CO_2 emissions are also carried out by increasing the storage capacity of CO_2 using CO_2-foam[16] and modifications for a CO_2 capture process using amine scrubbing [17].

II. RESEARCH METHOD

A. Thermodynamic Analysis of Power Plants

The principle of the Rankine Cycle working is to combine heat transfer between the components of the plant with the surrounding conditions. So the kinetic and potential energy can be ignored. Work analysis of Rankine cycles operates in steady state. The principle of conservation of mass and energy can be used to calculate the energy transfer from each component of the plant [18].

At a volume set in a steady state, the identity of the essence changes continuously, but the total amount that is there is constant at any time, so that the mass at the volume is set [18]:

$$\frac{dm_{cv}}{dt} = 0, \qquad (1)$$

Likewise the rate of energy transfer by heat and work which remains constant with time, so [18]:

$$\frac{dE_{cv}}{dt} = 0, \qquad (2)$$

Because kinetic energy and potential energy are ignored [18]:

$$\frac{W}{\dot{m}} = (h_{out} - h_{in}) \qquad (3)$$

with,

W= energy produced (kJ)
$\dot{m}$= mass flow rate (kg / s)
h_{out}= enthalpy of outlet (kJ / kg)
h_{in}= enthalpy of inlet side (kJ / kg)

B. *Calculation of Specific Fuel Consumption and Thermal Efficiency*

Based on SPLN No. 80 of 1989, the equation for calculating the specific consumption of fuel is as follows [19]:

$SFC = Q_f / kWh$……………………………………………….(4)

with,

SFC = Specific Fuel Consumption (Kg/kWh)

Q_f= amount of fuel Consumption (T/h)

kWh = amount of power generated (kWh)

Thermal efficiency is the ratio of energy produced by turbines to heat absorbed by boilers [18]:

$\eta = (W_{T\text{-}P})/Q_{in}$………………………………..………(5)

with,

W_T = Energy produced by turbines (kW)

W_P= Energy needed by the pump (kW)

Q_{in}= Amount of heat absorbed by the boiler (kW)

C. *Calculation of CO_2 emission*

Power plant that have fuel consumption data and have measured fuel quality (ultimate analysis or carbon content) can calculate CO_2 emissions using Method-2. Formula for calculating CO_2 emissions of fuel types presented in the formula below [7]:

$E_{CO_2} = F_{BB} x C_{ar} x FOx \, {}^{44}/_{12}$……………..................(6)

with,

E_{CO_2}= CO_2 emissions (tons)

F_{BB} = Fuel consumption in tons

C_{ar}= Carbon content, as received, percentage (weighted average)

FO=National default oxidation factor

44=CO_2 molecular weight

12=Atomic weight C

The research is to take the Heat Mass Balance data on a subcritical power plant with an installed capacity of 710 MW and a load capacity of 660 MW. Thermodynamic data in the form of pressure and temperature in each component of the plant will be converted into their enthalpy value using the *X Steam Table* made by Magnus Holmgren.

D. *Parameter Data*

The coal used in the power plant is sub-bitumious type which has a calorific value of High Heating Value (HHV) of 24306.98 kJ/kg with equivalent to 5810 kcal/kg. Ultimate analysis of the coal shows in Table 1.

TABLE I. ULTIMATE ANALYSIS OF COAL [20]

No	Parameter	Percentage Parameter (%)
1	Carbon (ar)	60.08
2	Hydrogen (ar)	4.92
3	Nitrogen (ar)	1.11
4	Sulfur (ar)	0.55

The heat mass balance scheme that is used as a reference for analysis is shown in Figs. 1. Numbering on the input and output side of the component will be explained further in table 2 along with the parameter values.

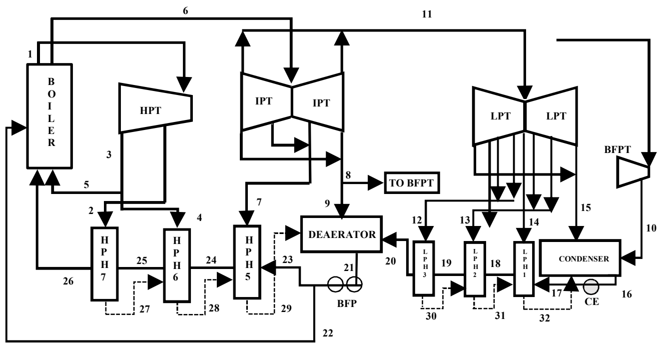

Fig. 1 Heat mass balance scheme [20]

The work data parameters according to Fig. 1 used for analysis, consist of mass flow, pressure, temperature, and enthalphy are shown in Table 2.

TABLE II. DATA FLOW THERMODYNAMIC OF THE STEAM POWER PLANT [20]

No	Component	Mass Flow (Kg/s)	P (bar)	T (°C)	Entalphy (kJ/kg)
1	**Boiler**				
	Inlet(26)	601.56	188.06	286.99	1266.9
	Outlet(1)	607.26	166.9	529.8	3285.2
2	***HPT***				
	Inlet (1)	607.26	166.92	529.8	3375.4
	Ekstraksi 1 (2)	57.2	72.35	413.55	3190.7
	Ekstraksi 2 (4)	41.48	39.84	326.22	3033.1
	Outlet (5)	508.8	40.31	328.27	3037.2
3	***Reheater***				
	Inlet (5)	508.8	40.31	328.27	3037.2
	Outlet (6)	508.8	36.63	547.42	3557.5
4	***IPT***				
	Inlet (6)	508.8	36.63	547.42	3557.5
	Ekstraksi 1 (7)	33.16	19.98	467.41	3396.3
	Ekstraksi 2 (8)	22.23	7.78	332.24	3127.4
	Ekstraksi 3 (9)	58.53	7.78	332.24	3127.4
	Outlet (11)	394.66	7.78	332.24	3127.4
5	***LPT***				
	Inlet (11)	394.66	7.78	332.24	3127.4
	Ekstraksi 1 (12)	16.67	1.11	199	2873
	Ekstraksi 2 (13)	23.89	1.09	102	2678.7
	Ekstraksi 3 (14)	10.15	0.23	63.1	2614.2
	Outlet (15)	343.95	0.172	56.8	2603.3
6	***Condenser***				
	Inlet 1 (15)	343.95	0.172	56.8	2603.3
	Inlet 2 (10)	22.23	0.08	42.7	2578.5
	Outlet (16)	416.89	0.07	41.62	2576.8
7	***LPH 1***				
	Inlet (17)	416.89	20.46	42.6	180.2
	Outlet (18)	416.89	0.2	59.7	249.9
	Ekstraksi Inlet (14)	10.15	0.23	63.1	2614.2
	Ekstraksi Outlet(32)	50.71	0.11	47.2	197.6
	Drain Inlet (31)	40.56	0.25	64.8	271.2
8	***LPH 2***				
	Inlet (18)	416.89	0.2	59.7	249.9
	Outlet (19)	416.89	0.88	96	402.2
	Ekstraksi Inlet (13)	23.89	1.09	102	2678.7
	Ekstraksi Outlet(31)	40.56	0.25	64.8	271.2
	Drain Inlet (30)	16.67	1.09	102.1	428
9	***LPH 3***				
	Inlet (19)	416.89	0.88	96	402.2
	Outlet (20)	416.89	7.41	119.6	502.5
	Ekstraksi Inlet (12)	16.67	1.11	199	2873
	Ekstraksi Outlet(30)	16.67	1.09	102.1	428
10	***Deaerator***				
	Inlet (20)	416.89	7.41	119.6	502.5
	Outlet (21)	607.26	7.63	169.09	712.5
	Ekstrasi inlet (9)	58.53	7.78	332.24	3127.4
	Drain inlet (29)	131.84	9.65	178.33	755.8

TABLE II. (continued)

No	Component	Mass Flow (Kg/s)	P (bar)	T (°C)	Entalphy (kJ/kg)
11	***HPH 5***				
	Inlet (23)	601.56	204.87	173.24	744.2
	Outlet (24)	601.56	20.86	214.52	918.4
	Ekstraksi Inlet (7)	33.16	19.98	467.41	3396.3
	Ekstraksi Outlet(29)	131.84	9.65	178.33	755.8
	Drain Inlet (28)	98.67	22.87	219.27	940.3
12	***HPH 6***				
	Inlet (24)	601.56	20.86	214.52	918.4
	Outlet (25)	601.56	38.7	248.4	1077.9
	Ekstraksi Inlet (4)	41.48	39.84	326.22	3033.1
	Ekstraksi Outlet(28)	98.67	22.87	219.27	940.3
	Drain Inlet (27)	57.2	43.72	255.68	1113.5
13	***HPH 7***				
	Inlet (25)	601.56	38.7	248.4	1077.9
	Outlet (26)	601.56	188.06	286.99	1266.9
	Ekstraksi Inlet (2)	57.2	72.35	413.55	3190.7
	Ekstraksi Outlet(27)	57.2	43.72	255.68	1113.5
14	***CEP Pump***				
	Inlet (16)	416.89	0.07	41.62	174.3
	Outlet (17)	416.89	20.46	42.6	180.2
15	***BFP Pump***				
	Inlet (21)	607.26	7.63	173.24	715.2
	Outlet (23)	601.56	204.87	173.24	744.2

III. RESULTS AND DISCUSSION

A. *Thermodynamic Analysis*

Based on Table 1, thermodynamic analysis can be carried out as follows [18] :

1) Calculation of Mass Fraction
   In a mixture, the mass fraction is the amount of mass of one substance, divided by the mass of the total mixture. The mass fraction shows the water content contained in the steam extracted from the turbine that enters the feedwater heater.
   a. Mass Fraction at HPH 7, y'_1=0.0910
   b. Mass Fraction at HPH 6, y'_2=0.0687
   c. Mass Fraction at HPH 5, y'_3=0.0548
   d. Mass Fraction at Deaerator, y'_4=0.0593
   e. Mass Fraction at LPH 3, y'_5=0.0298
   f. Mass Fraction at LPH 2, y'_6=0.044
   g. Mass Fraction at LPH 1, y'_7=0.0183

2) Heat absorbed by boiler
   The amount of heat per mass flow needed in the boiler is :

$$\frac{\dot{Q}_{boiler}}{\dot{m}} = 2108.5\ kJ/kg$$

   And in the reheater the heat demand per mass flow is:

$$\frac{\dot{Q}_{reheater}}{\dot{m}} = 472.95\ \text{kJ/kg}$$

3) Power generated by turbine
   In HPT produces as much power:

$$\frac{W_{HPT}}{\dot{m}} = 338.2\ \text{kJ/kg}$$

   In the IPT produces as much power:

$$\frac{W_{IPT}}{\dot{m}} = 396.1\ kJ/kg$$

   In LPT produces as much power:

$$\frac{W_{LPT}}{\dot{m}} = 474.3 kJ/kg$$

4) Power needed by the pump
   Power needed by CEP:

$$\frac{W_{CEP}}{\dot{m}} = 5.9\ kJ/kg$$

   Power needed by BFP:

$$\frac{W_{BFP}}{\dot{m}} = 29\ kJ/kg$$

5) Calculate Power Generated
   To calculate the power from a steam power system, mass flow rate data is needed to enter the boiler, i.e. $\dot{m}_1 = 607.26\ kg/s$, so:
   $W_{cycle} = 712.74\ MW$

6) Calculate Thermal Effisiency
   Thermal efficiency is the ratio of power generated with heat absorbed by the boiler, so the thermal efficiency is equal to:

$$\eta = 1173.7/2581.4$$
$$\eta = 0.4547 = 45.47\ \%$$

7) Calculate Fuel Consumption and *Spesific Fuel Consumpsion*
   With the boiler efficiency value data is 87.17% and the calorie value of coal (HHV) 24306.98 kJ / kg, the coal needed is:

$$m_{bb} = \frac{m_1 * (h_1 - h_{26}) + m_6 * (h_6 - h_5)}{\eta_{Boiler} * HHV}$$

   $m_{bb} = 72.92\ kg/s$ equivalent to 262.5 tons/hour.

   so SFC:
   SFC = Q_f *kWh*
   SFC = 262.5 / 712,74
   SFC = 0.368 kg/kWh

it means that to generate electricity 1 kWh requires fuel 0,368kg

Calculation CO_2 emissions:

$$E_{CO_2} = 262.5\ x\ 60.8\ x\ 0.98\ x \frac{44}{12}$$
$$E_{CO_2} = 566.7 \text{ tons/hr}$$
or 0.795 kg/kWh

It means that each 1 kWh power generation produces 0.795 kg CO_2 emissions

B. *Subcritical to supercritical Analysis*

Supercritical conditions are conditions where the steam pressure is above the critical point of water, namely pressure 221 bar and 374°C temperature. The principle difference between subcritical and supercritical is the superheater steam pressure produced by the boiler. If there is a change in the value of the fluid pressure, it will affect the enthalpy of the fluid.

If in the reference plant, where the steam pressure is 166.9 bar which means it is still a subcritical condition, we increase the steam pressure value in supercritical conditions, for example at 240 bar pressure with a fixed temperature of 529.8 °C, the enthalpy value of the boiler outlet will be 3285.2 kJ / kg. So that the heat absorbed by the boiler per mass flow becomes:

$$\frac{Q_{boiler}}{\dot{m}} = 2020\ kJ/kg$$

This value will affect the efficiency of the thermal cycle of the plant to:

$$\eta = \frac{(338.2 + 396.1 + 474.3) - (5.9 + 29)}{2020 + 472.9}$$
$$\eta = \frac{1173.7}{2492.9}$$
$$\eta = 0.4712$$
$$\eta = 47.12\ \%$$

From these calculations it can be proven that the plant operation in supercritical conditions will increase the thermal efficiency of the plant. The calculation results for various variations in pressure values can be shown in Table 3.

TABLE III. CALCULATION WITH PRESSURE VARIATION

Parameter	**Subcritical**				**Supercritical**			
Steam pressure (bar)	166.9	180	190	200	240	250	260	270
Coal (tons/hr)	262.5	260.9	259.7	258.4	253.2	251.9	250.5	249.2
SFC (kg/kWh)	0.368	0.366	0.364	0.363	0.355	0.353	0.352	0.350
CO_2 emissions (tons/hr)	566,7	563,3	560,6	557,9	546,6	543,8	540,9	537,9
Efficiency (%)	45.47	45.75	45.96	46.18	47.12	47.36	47.61	47.87
CO_2 emissions (kg/kWh)	0,795	0,790	0,787	0,783	0,767	0,763	0,759	0,755

Based on Table 3 it can be seen that assuming the efficiency of the boiler and the calorie value of the fuel remain increasing the pressure of the steam boiler will increase thermal efficiency, thereby reducing fuel consumption and CO_2 emissions.

At the actual condition steam pressure of 166.9 bar (subcritical) produces a thermal efficiency of 45.47% and CO_2 emissions of 566.7 tons / hour. CO_2 emissions will continue to decline, which is caused by a decrease in coal consumption in line with the increase in steam boiler pressure. At a steam pressure of 240 bar, which means in supercritical conditions, CO_2 emissions fell by 20.1 tons / hour to 546.6 tons / hour. With an increase in thermal efficiency of 1.65% causing a reduction in CO_2 emissions by 3.5 %, this is in accordance with the reference that an increase in efficiency of 1% will reduce the level of CO_2 emissions by approximately 2-3% [12].

IV. CONCLUSION

This study provides an overview of the potential for fuel savings and reduction of CO_2 emissions. Operation of the plant under conditions of higher boiler pressure will result in better thermal efficiency, so as to reduce fuel consumption while reducing CO_2 emissions. Using supercritical boiler in power plant will reduce the level of CO_2 emissions by approximately 3-4%. For further studies can be carried out with variations in the calorific value of coal.

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